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BSI Standards Publication

Semiconductor devices — Micro-electromechanical devices

Part 12: Bending fatigue testing method of thin film materials using resonant vibration of MEMS structures

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Semiconductor devices - Micro-electromechanical devices - Part 12: Bending fatigue testing method of thin film materials using resonant vibration of MEMS structures

(IEC 62047-12:2011)

Dispositifs à semiconducteurs - Dispositifs microélectromécaniques - Partie 12: Méthode d'essai de fatigue en flexion des matériaux en couche mince utilisant les vibrations à la résonance des structures à systèmes microélectromécaniques (MEMS)
(CEI 62047-12:2011)

Halbleiterbauelemente - Bauelemente der Mikrosystemtechnik - Teil 12: Verfahren zur Prüfung der Biege-Ermüdungsfestigkeit von Dünnschichtwerkstoffen unter Verwendung der Resonanzschwingungen bei MEMS-Strukturen
(IEC 62047-12:2011)

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Foreword

The text of document 47F/80/FDIS, future edition 1 of IEC 62047-12, prepared by SC 47F, "Micro-electromechanical systems", of IEC TC 47, "Semiconductor device", was submitted to the IEC-CENELEC parallel vote and approved by CENELEC as EN 62047-12:2011.

The following dates are fixed:

• latest date by which the document has to be implemented at national level by publication of an identical national standard or by endorsement	(dop)	2012-07-18
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In the official version, for Bibliography, the following note has to be added for the standard indicated:

IEC 62047-2:2006 NOTE Harmonized as EN 62047-2:2006 (not modified).

Annex ZA
(normative)
Normative references to international publications with their corresponding European publications

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

NOTE When an international publication has been modified by common modifications, indicated by (mod), the relevant EN/HD applies.

Publication	Year	Title	EN/HD	Year
IEC 62047-3	2006	Semiconductor devices - Micro-electromechanical devices - Part 3: Thin film standard test piece for tensile-testing	EN 62047-3	2006
ISO 12107	-	Metallic materials - Fatigue testing - Statistical planning and analysis of data	-	-

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SEMICONDUCTOR DEVICES – MICRO-ELECTROMECHANICAL DEVICES –

Part 12: Bending fatigue testing method of thin film materials using resonant vibration of MEMS structures

1 Scope

This part of IEC 62047 specifies a method for bending fatigue testing using resonant vibration of microscale mechanical structures of MEMS (micro-electromechanical systems) and micromachines. This standard applies to vibrating structures ranging in size from 10 μm to 1 000 μm in the plane direction and from 1 μm to 100 μm in thickness, and test materials measuring under 1 mm in length, under 1 mm in width, and between 0,1 μm and 10 μm in thickness.

The main structural materials for MEMS, micromachine, etc. have special features, such as typical dimensions of a few microns, material fabrication by deposition, and test piece fabrication by means of non-mechanical machining, including photolithography. The MEMS structures often have higher fundamental resonant frequency and higher strength than macro structures. To evaluate and assure the lifetime of MEMS structures, a fatigue testing method with ultra high cycles (up to 10^{12}) loadings needs to be established. The object of the test method is to evaluate the mechanical fatigue properties of microscale materials in a short time by applying high load and high cyclic frequency bending stress using resonant vibration.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 62047-3:2006, *Semiconductor devices – Micro-electromechanical devices – Part 3: Thin film standard test piece for tensile testing*

ISO 12107, *Metallic materials – Fatigue testing – Statistical planning and analysis of data*

3 Terms and definitions

For the purposes of this document the following terms and definitions apply

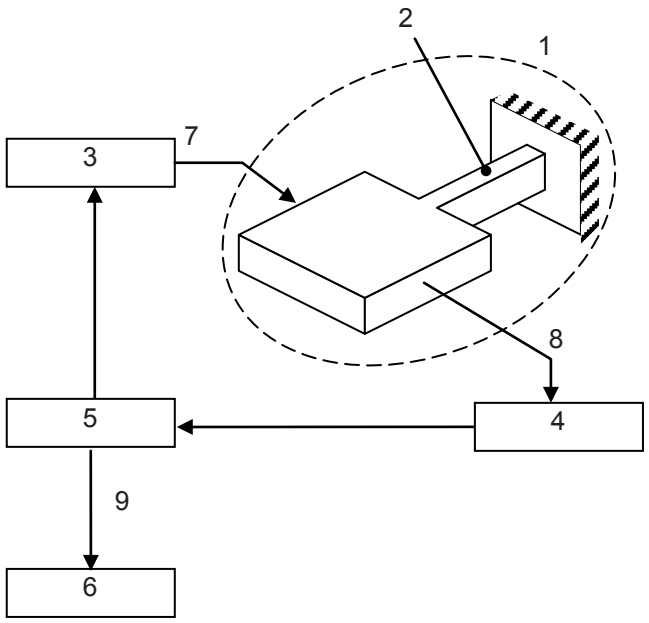
3.1
amplitude
one-half the algebraic difference between the maximum value and minimum value in a loading cycle

3.2
load ratio
algebraic ratio of the maximum value and minimum value of the load of a cycle

3.3
S-N curve
plot of stress or strain (S) against the number of cycles (N) to failure

3.4
reference strength:
static strength or instantaneous failure strength

3.5
instantaneous failure strength
failure strength of quasi-static test or resonant vibration test at rapid amplitude growth



Key

1 Specimen
2 Test part
3 Actuator
4 Sensor
5 Controller
6 Recorder
7 Force
8 Displacement or strain
9 Amplitude and frequency

Figure 1 – Block diagram of the test method

4 Test equipment

4.1 General

The test equipment shall be capable of generating resonant vibration with constant amplitude and stable frequency to the test structure. A block diagram of the test equipment is shown in Figure 1. The test equipment consists of an actuator for oscillation, a sensor for amplitude detection, a controller for maintaining the resonant vibration at a constant amplitude, and a recorder for monitoring.

The amplitude control method is classified as follows.

a) Constant strain control

Applied strain in the test part is maintained at constant. It can be applied for elastic or inductile materials.

b) Constant stress control

Applied stress in the test part is maintained at constant. Load monitoring and closed loop control is crucial for the method.

4.2 Actuator

The actuator shall be capable of applying oscillation force of the necessary amplitude and frequencies along the required direction. Various kind of actuators can be used, e.g., electrostatic, piezoelectric, thermal, and electromagnetic actuators. The actuator may be installed in the test structure, as discussed in 5.1.

4.3 Sensor

The sensor shall be capable of measuring the movement of the specimen to determine the stress amplitude (for constant stress amplitude testing) or the strain amplitude (for constant strain amplitude testing) to the test part of the specimen.

The sensor and its associated electronics shall be accurate to within 1 % of the range of the stress or strain amplitude.

The sensor should measure the movement continuously, in order to maintain a constant vibration and detect failure effectively. If the specimen is an elastic material and will not show the change in the vibrating properties, however, it is permissible to measure the movement at regular time intervals.

The movement is detected by measuring displacement of the test structure or the stress or strain in the test structure. Clause A.2 shows a method for detecting rotational displacement of the mass from changes in capacitance. Clause B.2 shows a method using a strain gauge integrated in the specimen. Clause C.2 shows a method for detecting displacement of the mass using a non-contact displacement gauge.

4.4 Controller

The controller shall be capable of generating the oscillation signal to the actuator from the movement signal from the sensor, in order to maintain the required resonant vibration. During testing, the amplitude and frequency of the specimen shall be maintained at a constant level. One of the following methods should be applied for the specimen, depending on the vibration characteristics.

a) Closed loop method

The frequency and amplitude of the oscillation signal applied to the specimen shall be controlled to follow changes in the resonant frequency. In most cases, the signal applied to the actuator is generated from the movement signal of the specimen. A self-excited oscillation circuit or phase-locked loop circuit can be used as a means for maintaining the resonant frequency. An automatic gain control circuit (AGC) can also be used to maintain a constant amplitude by changing the amplitude of the oscillation signal based on the detected amplitude.

b) Open loop method

Elastic or inductile materials that show a linear response but no plastic deformation may be tested using an open loop method. This test may be performed by stopping at regular intervals and measuring the resonant characteristics, or by actuating the test structure from the start to the end of testing at a predetermined resonance frequency and oscillation signal amplitude.

The stability of the frequency and amplitude shall be maintained throughout the test to within ± 3 % of the desired value.

4.5 Recorder

The test equipment shall include a recorder for collecting the “record data” indicated in 8.6.

4.6 Parallel testing

The test may be conducted in parallel with a number of equipment units. In this case, steps should be taken to eliminate mutual electrical or mechanical interference among the equipment units.

5 Specimen

5.1 General

The specimen shall be capable of applying a constant and high-load amplitude to the test part via resonant vibration. Examples of specific structures are shown in the Clauses A.1, B.1, and C.1.

It is permissible to integrate a mechanism in the specimen for actuating or for sensing the movement of the specimen. An example of a structure integrating mechanisms for actuation and detecting amplitude is shown in Annex A.1. An example of a structure integrating a mechanism for detecting amplitude only is shown in Annex B.1.

5.2 Resonant properties

The specimen shall have resonance characteristics that enable the application of the required deformation (mode of vibration) in the specific frequency (resonance frequency) of the specimen. The resonant frequency should preferably be more than 1 000 Hz, in order to obtain a large number of the cycles in a short time. The quality factor of the specimen should be more than 100, in order to obtain a large amplitude. Steps should be taken to ensure, within this resonance frequency, that the specimen will not vibrate in a vibration mode different from that used in the test. For example, there should be no other resonant modes close to the mode used for testing.

5.3 Test part

The specimen shall have a test part in which stress sufficient to induce failure occurs. When the test is performed to evaluate the reliability of the actual device, the deformation in the test part at resonant vibration (in-plane and out-of-plane bending) shall be the same as that of the actual device. If only low stress can be applied to a structure similar to the actual device, a notch or another means may be introduced to concentrate the stress in the targeted section of the test part.

5.4 Specimen fabrication

Refer to Clause 5 of IEC 62047-3 when manufacturing the test part of the specimen. The specimen should be fabricated by the same method as the target MEMS device for reliability evaluation is fabricated. Furthermore, the same shapes, dimensions, and multilayer film structures should be used.

6 Test conditions

6.1 Test amplitude

The test amplitude should be specified from the appropriate reference strength of the specimen. The reference strength should be determined through the methods in 7.1. One of the following procedures should be chosen for determining the test amplitude during testing, based on the reference strength.

a) Constant amplitude of 100 % of the reference strength:
   to evaluate the fatigue life at a certain amplitude.
b) Decrease the amplitude gradually from a high level:
   for obtaining an S-N curve in a short time.
c) Increase the amplitude gradually from a low level:
   for obtaining an S-N curve when the number of test parts is limited.

As a reference for determining the test amplitude, example of experimental data and analysis of fatigue testing for silicon are shown in Annex D. For details on the testing of metal materials, refer to ISO 12107.

The decrease and increase step of the test amplitude for the procedures b) and c) should be selected preferably close to the standard deviation of measured reference strength.

6.2 Load ratio

The load ratio of the test method can be taken to be -1, as the quality factor (Q) of the resonant vibration is high enough (10 or more) to achieve an amplitude too high to apply by (quasi-)static testing methods.

6.3 Vibration frequency

The frequency shall be the resonant mode at which the test part is in the required stress state specified in 5.3, or a frequency close to it.

6.4 Waveform

The waveform of the displacement of the specimen and the stress and strain of the test part can be regarded as sinusoidal, irrespective of the actuating waveform

6.5 Test time

The test time shall be specified as the time at which the test ends, even if the specimen has not failed by that time. The test time can be determined as the number of the test cycles, based on the vibration frequency. For tests conducted on materials with lifetime characteristics which are frequency-independent, such as silicon, the test cycles are chosen as the stress cycles applied on the actual devices in their lifetimes. See Annex D.

6.6 Test environment

The test environment should be maintained at a constant temperature and humidity.

7 Initial measurement

7.1 Reference strength measurement

The reference strength shall be measured prior to the fatigue test. Specimens used for measurement of the reference strength should be made of the same materials, and by the same processes, as the test part to be tested. Care shall be taken when using a specimen of a different shape. If such a specimen is used, it should show the same failure mode, and the size effect on the measured strength should be considered.

The reference strength should be determined using one of the following tests.

a) Quasi-static test

The failure strength measured by conducting quasi-static testing is set as the reference strength.

b) Instantaneous fatigue test

The maximum amplitude in the instantaneous fatigue test is set as the reference strength. In this test, the amplitude is rapidly increased up to the point of specimen failure by the same method used for the fatigue test. This method may be chosen when it is difficult to use a specimen of a different shape, or when it is difficult to apply a static load.

c) Stress analysis

The reference strength is determined using either simulation or theoretical analysis. This method can be chosen when a reference strength is difficult to determine experimentally. The amplitude at which the maximum stress in the specimen reaches the failure strength is set as the reference strength. The failure strength can be taken from published papers or other available data. The reported strength should be chosen carefully, as some materials have size effect in failure strength and environmental effects under variable temperatures, humidity levels, and so on. It is thus desirable to refer to the strength values in the literature in order to keep conditions as close as possible to those in the life test to be conducted.

Given the large variation in the strength of brittle materials such as single crystal silicon, it is preferable to obtain strength data for no less than 10 specimens when measuring the reference strength experimentally, and to adopt a statistically processed value (for example, 50 % failure stress from Weibull analysis or an arithmetical average) as the reference for stress or strain in the resonant oscillation test.

7.2 Frequency response test

The resonant properties of the specimens shall be measured prior to the fatigue test. When the resonant properties vary among specimens and the controller needs tuning, the resonant properties of all of the specimens should be measured.

The frequency response test is used to measure the resonant properties. The oscillation signal is applied from a function generator and the frequency of the signal is swept around the expected resonant properties to find the actual resonant frequency. The load applied in this response test shall be small enough to ensure that the measurements for the fatigue test are unaffected. If the effect cannot be ignored, the number of load cycles applied in this response test should preferably be added to the fatigue test data.

8 Test

8.1 General

The fatigue test shall be conducted by applying resonant oscillation at the predetermined oscillation amplitude to the specimen. The test ends when the specimen fails or the predetermined test time is reached.

8.2 Initial load application

The increasing rate of the amplitude should be specified properly at the start of the fatigue test. Because the test is conducted in resonance and the quality factor is high, the amplitude cannot reach the test amplitude without delay. If the amplitude increases too rapidly, it can result in an overshooting of the amplitude and unexpected failure at the start of the test. If, on the other hand, too much time is allowed for the increase in amplitude, the test result can be affected. The initial load applied in these procedures should be carefully controlled to ensure that measurement results of the lifetime test are unaffected. When some effect is conceivable, the procedures for increasing the amplitude should be described in the test report.

8.3 Monitoring

The vibration of the specimen shall be monitored continuously during the test to detect the specimen failure. One method for this test monitoring is to monitor the vibration frequency and/or amplitude. It is also desirable to record the changes in the vibration frequency and amplitude at proper time intervals. If the system lacks a monitoring function, the specimen may be monitored by stopping the fatigue test at certain intervals of time and conducting the frequency response test in 7.2.

8.4 Counting the number of cycles

The number of cycles of the fatigue test shall be counted using a counter. Alternatively, the cycles may be calculated by multiplying the vibration frequency by the time from the start of testing.

8.5 End of the test

The test shall end at the point of specimen failure, or when a predetermined loading time or a predetermined number of cycles has elapsed.

Specimen failure is defined as the following:

a) fracture of the test part;

b) a certain percentage change in the amplitude;

c) a certain change in the oscillating frequency.

8.6 Recorded data

The failure of the specimen shall be recorded. The oscillation amplitude and frequency of the specimen and the temperature and humidity of the testing environment should be measured at certain intervals of time during the test.

9 Test report

The test report shall include the following information.

- Mandatory

  a) reference to this International Standard, i.e. IEC 62047-12

  b) test piece material
     – in the case of a single crystal: crystallographic orientation

  c) method and details of test piece fabrication
     – method of thin film deposition
     – fabrication processes
     – heat treatment (annealing) conditions

  d) shape and dimensions of test piece

  e) test equipment
     – oscillation method (self-oscillation, external oscillation)
     – initial load application method
     – amplitude control method
     – test monitoring method (amplitude, frequency, number)

f) fatigue test conditions
   - reference strength, and its measurement method
   - mean stress (in the case of displacement control, mean displacement)
   - stress amplitude (in the case of displacement control, displacement amplitude)
   - load ratio
   - testing environment (temperature and relative humidity)
   - wave form (sinusoidal)
   - frequency

g) fatigue test result
   - number of samples
   - number of applied cycles to failure. If the test piece is not fractured during a predetermined number of cycles, the number of cycles and the description “no failure” should be noted.
   - definition (type) of failure

- Optional

a) purpose of the test
   - motivation or object

b) microstructure
   - in the case of polycrystalline thin film: texture and grain size

c) internal stress

d) mask design
   - resolution of mask drawing and lithography

e) surface roughness of test piece
   - photographs of the finished test part, along with any surface treatment (cleaning procedure)

f) brief description of fracture characteristics

g) detailed test results
   - S-N curve (S is peak stress or stress amplitude)
   - fatigue strength, statistical processing (fatigue probability)
   - amplitude history
   - fractograph.

Annex A
(informative)

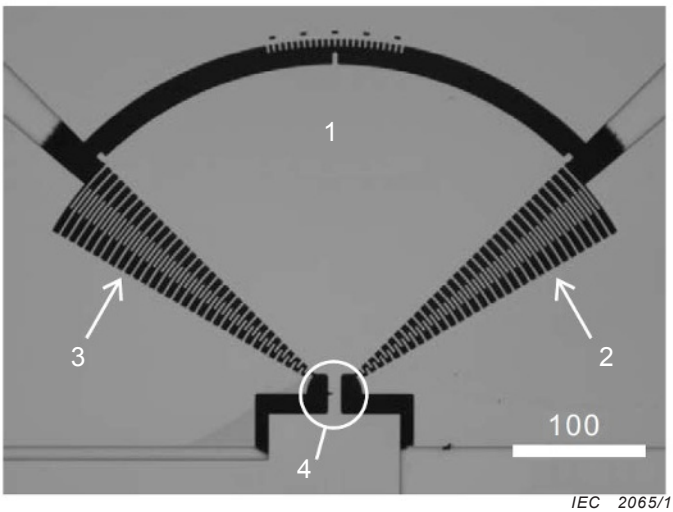
Example of testing using an electrostatic device with an integrated actuation component and displacement detection component

A.1 Specimen

The specimen consisted of a flexible beam test part and a fan-shaped mass fabricated by dry etching a thin film of single crystal silicon as shown in Figure A.1. One end of the flexible beam is fixed to the mass and the other is fixed to a substrate. An electrostatic comb-drive actuator is connected to the mass, and in-plane bending can occur in the flexible beam. A comb electrode attached to the mass outputs a signal proportional to the displacement, and the mass has a deflection scale that can be read by microscope. Since the test material is used for the electrostatic actuator and sensor, the test material is a conductive material.

The resonance frequency of the specimen is determined by the moment of inertia of the mass and the flexural rigidity of the flexible beam. The fundamental resonance frequency of the in-plane vibration of the test part varied between 38,75 kHz and 39,71 kHz. This variation resulted mainly from the less-than-uniform thickness of the thin film formed on the structure. Based on a measurement of the displacement response when an external signal was applied to the actuator, the *Q* value of the oscillator in the atmosphere was estimated to be 370. To increase the *Q* value of the oscillator, the bottom surface of the oscillator substrate was removed by etching. No resonance other than first in-plane vibration was observed in nearby frequencies. The test was performed at the resonance frequency of the in-plane vibration mode.

Dimensions in micrometres



Key

1 Resonator
2 Actuator
3 Sensor
4 Test piece

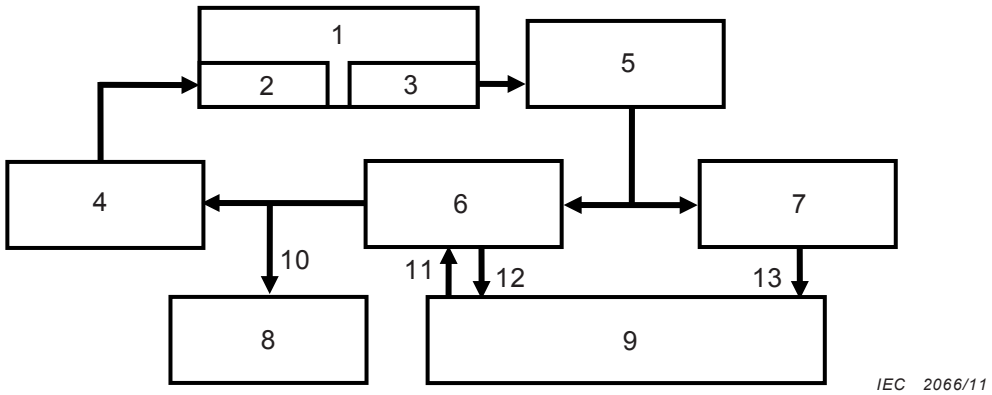
Figure A.1 – Microscope image of the specimen

The test part was composed of a single crystal silicon with an SOI active layer of 10 μm in width, 30 μm in length, and 5 μm in thickness, and etched surfaces at the sides. With in-plane bending deformation, the stress on the sidewall surfaces was a potential cause of failure. To eliminate the influence of surface roughness on the sidewall, steps were taken to obtain a

side surface as smooth as possible by lithography and etching. As it was conjectured that sufficient stress to cause failure could not be applied to test parts with a beam structure only, a notch of 4 μm deep was introduced into the middle of one side of the test part. The tip of the notch was a half circle with a radius of 0,5 μm, and the behavior of the stress concentration was evaluated by the finite element method.

A.2 Test equipment

The test equipment for applying resonant oscillation to the specimen consisted of an electric circuit only, as the actuation and detection mechanisms were built into the specimen. The block diagram of the test equipment is shown in Figure A.2. Resonant vibration was induced in the specimen by a self-oscillation method.



Key

1 Test piece
2 Actuator
3 Sensor
4 Driver
5 Oscillating circuit
6 Automatic gain controller
7 Frequency-voltage converter
8 Oscilloscope
9 Control PC
10 Oscillating waveform monitor
11 Amplitude reference
12 Amplitude output
13 Frequency output

Figure A.2 – Block diagram of test equipment

Eight sets of test equipment were manufactured, to work in parallel. When the power supply and circuit board are shared in this type of setup, stable oscillation can be disrupted by electrical interference. Therefore, in conducting the tests in parallel, the electrical coupling was reduced by selecting specimens of slightly different frequencies.

The actuation component amplifies a drive signal whose amplitude and phase are adjusted from the displacement signal to realize feedback oscillation. The actuation signal is amplified with a biased high voltage amplifier and applied to the electrostatic comb actuator. The drive signal voltage during stable oscillation was V_{pp} = 20 V to V_{pp} = 40 V.

The displacement amplitude of the specimen was measured by detecting the capacitance of the comb electrodes. The capacitance of the comb was measured with a charge amplifier, and an electrical signal proportional to the angular displacement was obtained. The amplitude was observed simultaneously by reading the deflection scale by microscope, thus enabling calibration of the electrical signal.

As the force applied to the test part is immeasurable in this technique, the stress applied to the test part is evaluated by finite element analysis based on the measured angular displacement of the mass.

With the use of the self-excited oscillation circuit, the specimen vibrates at the resonance frequency. To keep the displacement of the specimen at a constant level, an automatic gain controller (AGC) is built into the oscillation circuit. The amplitude of the specimen can be controlled by software, as the reference voltage of the AGC is controlled using the analog voltage output from a computer.

If the value set for the AGC amplitude of the vibration control circuit is raised quickly, the delay in mechanical resonance due to the high *Q* value can destabilize the oscillation. Unstable vibration starts after several dozen milliseconds, and a few milliseconds later the test part will fail due to vibration overshoot. To prevent this, the value set for the AGC amplitude was raised linearly over 10 s by computer control. This approach resulted in an increase in the oscillation amplitude with stable vibration, and the setting value was reached without overshoot. The time required to raise the amplitude was short in comparison with the fatigue life, and thus was excluded from the test results.

With this test method, an electric displacement signal is the output to be observed. As long as this signal is sinusoidally stable, the specimen can be presumed to be vibrating stably, without failure. When the test part fails, the signal shows a sudden break in the sinusoidal wave. The waveform of the displacement signal was observed over a short time with an oscilloscope, while the long-term displacement signal was recorded by taking the detected amplitude of the AGC at set intervals. The temperature and humidity were measured at the same time.

The measured amplitude signal and frequency signal were recorded every 1 s by an analog-digital converter circuit to determine whether or not failure had occurred. In some tests, the displacement signal at the moment of failure was recorded by a digital oscilloscope (recording was triggered by a drop in the displacement signal).

A.3 Test conditions

Because of the difficulty of performing a static or quasi-static strength test, in this test system, the reference amplitude for this specimen was determined by preliminary fatigue testing. The stress ratio was taken as –1, since the same displacement was consistently observed at both sides in the microscope observation of the amplitude scale.

The vibration frequency was measured with a frequency-voltage convertor. Frequency changes higher than the resolution (about 200 Hz) were not observed at any point during the test. The test time was 168 h. The test was conducted with the test parts placed in a temperature- and humidity controlled chamber (temperature 23,0 °C ± 0,1 °C, humidity 49 % RH to 51 % RH and 24 % RH to 27 % RH).

A.4 Initial measurement

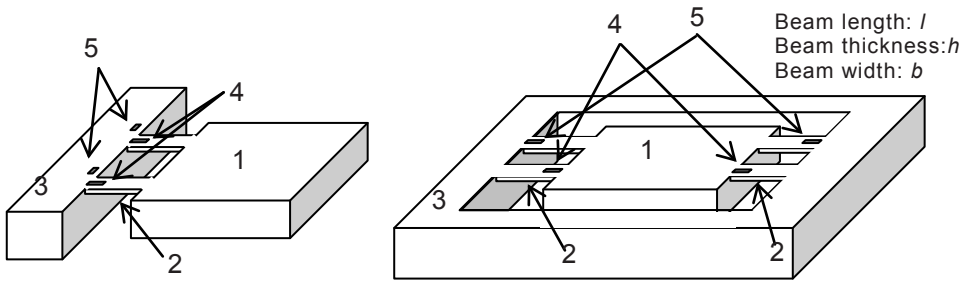
The only initial measurement was a frequency response test of the specimen. The test was performed by applying a sinusoidal signal to the actuator from an external oscillator and observing the displacement output. The resonance frequency of all specimens was inspected prior to the lifetime test. In addition, self-oscillation and stability were checked over a short time (about 1 min) with the specimens configured as a feedback circuit. The oscillation amplitudes for these initial measurements were kept below the minimum amplitude for the lifetime tests, and thus were not thought to have effects on the test results. None of the specimens that showed stable vibration failed during the initial measurement.

Annex B
(informative)

Example of testing using an external drive and a device with an integrated strain gauge for detecting displacement

B.1 Specimen

The specimen is fabricated by the bulk micro-machining of a single crystal silicon wafer, as shown in Figure B.1. In this system, the mass is supported by two or four beams, displaced vertically from the substrate surface. Four strain gauges are fabricated in the beams and connected as a Wheatstone bridge. Changes of resistance due to deformation of the beams can be detected as voltage output. The displacement is monitored from the output of the strain gauge bridge. A bridge connection is formed by arranging gauges pairwise, where the strain is generated toward the opposite direction. The relationship between the displacement and bridge output is calibrated in advance.



(a) cantilever type (b) double supported type

IEC 2067/11

Key

1 Resonator
2 Test piece
3 Frame
4 Strain gauge (positive polarity)
5 Strain gauge (negative polarity)

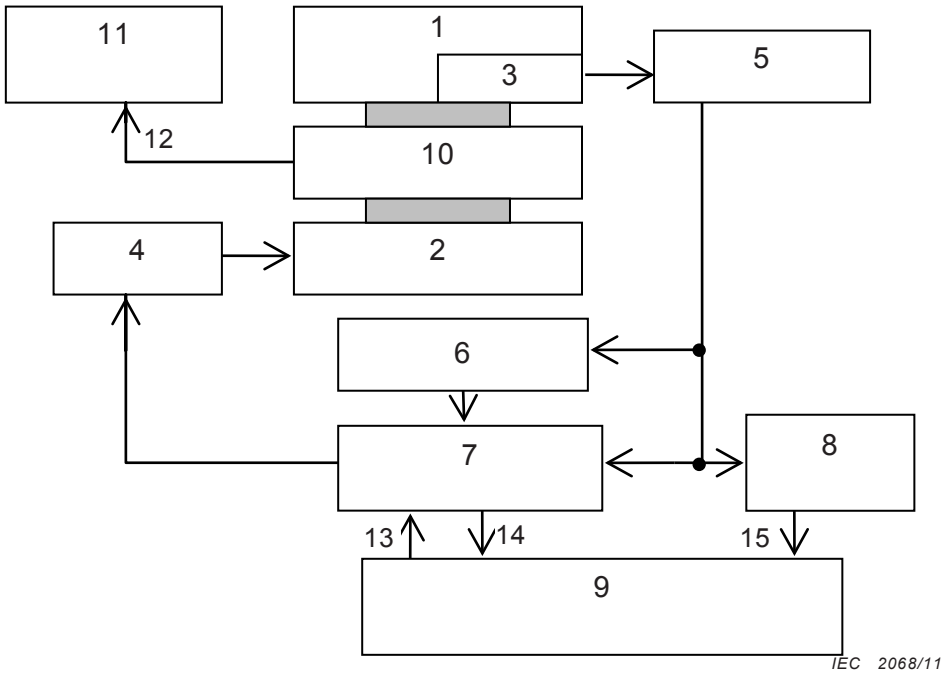
Figure B.1 – The specimens' structure

The test part is made from single crystal silicon by anisotropic wet etching. Strain gauges are formed in the surface of the specimen for detecting amplitude. The maximum stress occurring in the specimen is calibrated in advance by finite element analysis of the relationship between the maximum stress and the vertical displacement of the mass. The maximum stress can be evaluated from the voltage output of the strain gauge.

As an example, a doubly supported type single crystal silicon resonator was tested. The mass was 1 mm wide, 1,5 mm long, and 0,5 mm thick. The four suspending beams were 500 μm long, 200 μm wide, and 20 μm thick. The observed resonance frequency of the specimen was 8,5 kHz to 8,9 kHz.

B.2 Test equipment

Block diagram of the test equipment is shown in Figure B.2. The sensor is integrated with the specimen, as described in Clause B.1. A stacked piezoelectric actuator is used as the actuator. The specimen is mounted on the metal package and placed over the piezoelectric actuator. Applied acceleration to the resonator is monitored by a vibrometer.



Key

1 Test piece
2 Actuator
3 Sensor
4 Driver
5 Amplifier
6 Phase locked loop circuit
7 Automatic gain controller
8 Frequency-voltage converter
9 Control PC
10 Vibrometer
11 Oscilloscope
12 Oscillating waveform monitor
13 Amplitude reference
14 Amplitude output
15 Frequency output

Figure B.2 – Block diagram of test equipment

A driving circuit controller generates an actuating signal from the displacement signal to oscillate resonant vibration. The actuating signal is generated by a phase-locked loop (PLL) circuit. An automatic gain control circuit is used to maintain a constant amplitude set by a PC recorder. The PC was used to monitor the amplitude obtained from the control circuit and the voltage output proportional to the frequency. Eight sets of this system were operated in parallel.

Care shall be taken in fixing the specimen on the actuator, as the vibration characteristics vary significantly according to the state of bonding.

Measurements of the displacement signal and frequency-converted signal were recorded every 1 s by the computer's analog signal input circuit, to observe whether or not failure had occurred. When the amplitude diverged by 20 % beyond the set range, it was recorded and the test part was judged to have failed.

B.3 Test conditions

The test was performed with amplitudes at 60 % to 95 % of the reference strength. The stress ratio was taken as -1.

The fatigue test was performed at resonant frequency. After encountering nonlinear vibration in some cases in the large amplitude domain, the test was also performed at frequencies slightly lower than the resonance.

The test time was 35 h (about 10^9 cycles).

The specimen was installed in a humidity-controlled clean room (temperature 23,0 °C ± 0,5 °C, humidity (50 ± 1) % RH or a sealed container. Testing was conducted with (1) low humidity achieved with desiccant (dry air: temperature 23,0 °C ± 0,5 °C, humidity (50 ± 1) % RH), (2) N_2 gas flowing (low humidity nitrogen: temperature 23,0 °C ± 0,5 °C, humidity (50 ± 1) % RH, and (3) N_2 gas bubbled through distilled water (temperature 23,0 °C ± 0,5 °C, humidity (50 ± 1) % RH.

B.4 Initial measurement

The reference strength measurements were taken by two methods. The first was a quasi-static test in which an indenter pressed down onto the center of the mass to induce failure. The second method was performed by increasing the amplitude gradually with the test equipment and measuring the amplitude at the point of failure. Though the former was a quasi-static approach, the resonant oscillation and mode of deformation differed. The second method, meanwhile, should be considered a kind of fatigue test. The amplitude was set with the average intensity obtained from these strength tests as the standard.

In the frequency response test of the specimen, a signal was applied to the actuator from an external oscillator and measured. The resonance frequencies of all specimens were determined. In addition, self-oscillation and stability was checked over a short time (about 1 min) with the specimens configured as a feedback circuit.

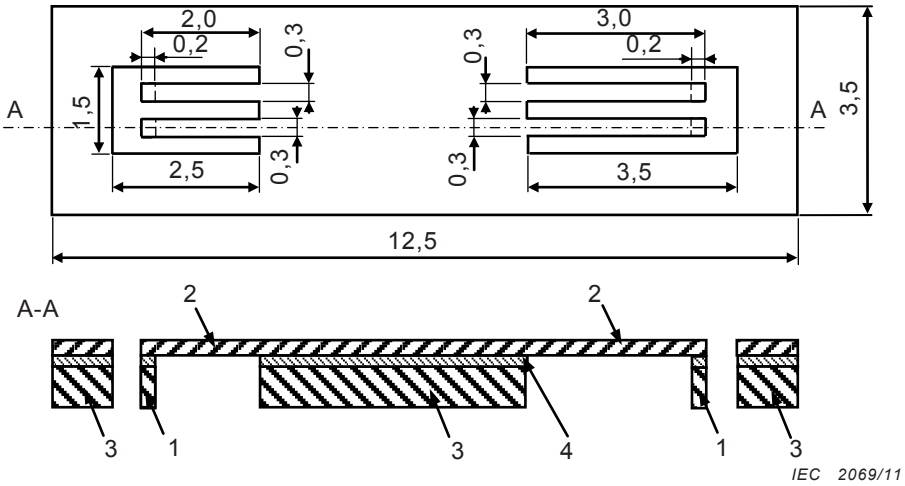
Annex C
(informative)

Example of electromagnetic drive out-of-plane vibration test (external drive vibration test)

C.1 Specimen

A lifetime test for a cantilever-shaped specimen was performed using resonance generated by an external drive source such as an electromagnetic drive, then subjecting the fixed end of the specimen to cyclic loading. This approach enables fatigue life testing of cantilever-shaped components, the shapes of which are close to those of actual MEMS devices. It thus becomes advantageous to make the dimensions of the specimens close to those of the application devices. Figure C.1 shows an example of a specimen.

Dimensions in millimetres



Key

1 Resonator
2 Test piece (single crystalline silicon with thickness of 2 μm)
3 Frame (single crystal silicon)
4 Sacrificial layer (silicon dioxide)

Figure C.1 – Specimen for out-of-plane vibration testing

The resonant frequency of the cantilever-shaped specimen is roughly estimated by Equations (C.1) and (C.2). Even so, the actual value should also be measured experimentally.

$$f_c = 0{,}16154 \times \frac{h}{L^2}\sqrt{\frac{E_e}{\rho}} \qquad \text{(C.1)}$$

where

f_c is the resonant frequency of the cantilever;

h is the thickness of the test part;

L is the length of the test part;

E_e is the effective Young's modulus;

ρ is the material density.

$$E_{\mathrm{e}} = \frac{E}{1-\nu^2} \tag{C.2}$$

where

E_{e} is the effective Young's modulus;

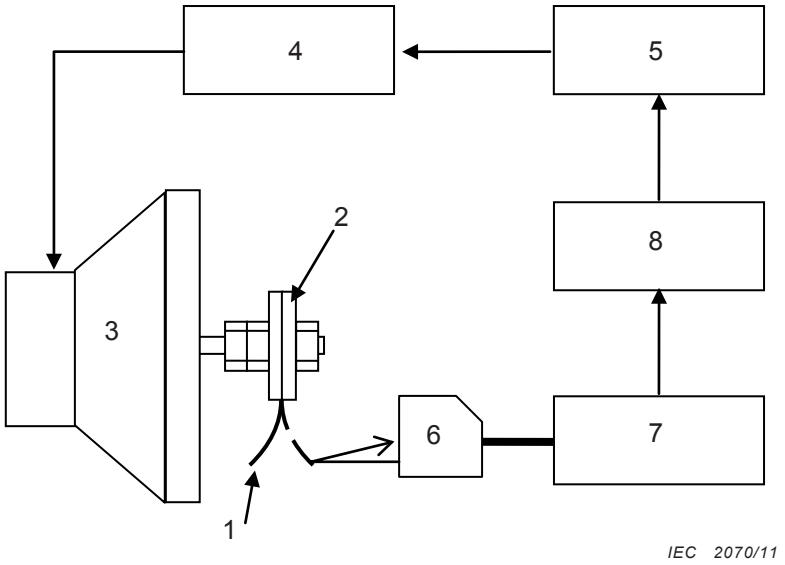
E is the Young's modulus;

ν is the Poisson's ratio.

The resonance of test part is enhanced by attaching a mass to the end of the cantilever, as shown in Figure C.1.

C.2 Test equipment

Cyclic tensile and compressive stresses were applied to the fixed end of the test part by applying the vibration at the resonant frequency through the electromagnetic driver (Figure C.2). An audio speaker and amplifier were used as an electromagnetic drive. A sinusoidal wave is suitable for the drive waveform. A non-contact displacement measurement system such as a laser displacement meter should be used to measure the cyclic displacement of the test part.



Key

1 Test piece
2 Test piece holder
3 Speaker (actuator)
4 Amplifier
5 Function generator
6 Sensor head
7 Laser displacement sensor
8 Control PC

Figure C.2 – Block diagram of test equipment

Fatigue testing is conducted by adjusting the amplitude of the resonance frequency of the specimen. Because this testing method is basically displacement-controlled, finite element analysis can be applied to determine the stress at the fixed ends, if necessary. And because the test extends over a long period of time, the system should be equipped with mechanisms for detecting test part failures and equipment to measure the testing time.

The waveform of the displacement sinusoidal wave of the electromagnetic driver can show distortion when the input power to the driver reaches excessive levels. The fatigue test should

be performed at a power below that tolerated by the driver. This is accomplished by providing a waveform monitor during testing. If the specimen does not fail at the maximum drive amplitude of the driver, a stress concentration site such as a notch may be introduced near the fixed ends of the specimen. In this case, the dimensions of the notch should be chosen properly by actual testing or finite element analysis.

C.3 Initial measurement

The initial failure displacement of the test part was measured by applying a vibration strong enough to fracture the test part immediately. The testing displacement should be chosen properly, based on the initial fracture displacement.

The resonant frequency of the test part should be measured by sweeping frequencies from low to high under an amplitude as low as possible relative to the initial failure displacement.

Annex D
(informative)

Theoretical expression on fatigue life of brittle materials based on Paris' law and Weibull distribution

D.1 Stress and fatigue life relationship

The fatigue properties of brittle materials can be explained appropriately using Paris' law if defects in the material are modeled as cracks with equivalent length. By applying Paris' law, the well-known equivalent fatigue crack propagation extension theory is formulated as described below.

NOTE The effect of the load (stress) ratio on fatigue properties of silicon has not taken into account in the following analysis.

Paris' law is typically shown as follows.

$$\frac{da}{dN} = C\Delta K^n = C'\left(\frac{\Delta K}{K_c}\right)^n \tag{D.1}$$

where

a is the crack length;

N is the number of cycles;

C, C', and n are constants;

ΔK is the range of the stress intensity factor corresponding to stress amplitude;

K_c is the fracture toughness.

Thus, the length of the cracks equivalent to damage are assumed to be small in comparison with the dimension of the test parts, and the stress intensity factor can be evaluated theoretically as follows.

$$K = \beta\sigma\sqrt{\pi a} \tag{D.2}$$

where

K is the stress intensity factor;

a is the crack length;

β is the coefficient related to the crack shape;

π is the number 3,141 592 6… .

σ is the applied stress.

If the crack length is sufficiently small in relation to the test part, coefficient β is equivalent to that of a surface crack in a semi-infinite body, and thus can be considered constant. By simply integrating Equation (D.1), the relationship between fatigue life N and applied stress σ can be obtained by the following equation,

$$N-1=\frac{a_{c0}}{C'}\frac{2}{2-n}\left(\frac{\sigma}{\sigma_{c0}}\right)^{-2}\left[1-\left(\frac{\sigma}{\sigma_{c0}}\right)^{2-n}\right] \quad \text{(D.3)}$$

where

N is the number of cycles;

a_{c0} is the equivalent initial crack length;

σ_{c0} is the static strength;

C' and n are constants;

σ is the applied stress.

If these variables are assigned to the right side of Equation (D.2), a stress intensity factor corresponding to toughness is obtained.

D.2 Fatigue lifetime distribution

If fatigue life is as shown in Equation (D.3), the variation in the fatigue life should be explicable in terms of the variation of the equivalent initial crack length. The variation in static strength is postulated as the two-parameter Weibull distribution expressed in the following equation,

$$F=1-\exp\left[-\left(\frac{\sigma}{\sigma_0}\right)^m\right] \quad \text{(D.4)}$$

where

F is the cumulative fracture probability;

m is the Weibull modulus;

σ_0 is the scale parameter;

σ is the applied stress.

When Paris' law is applied to this distribution by substituting the stress with equivalent crack distribution assuming constant toughness, the cumulative fracture probability can be calculated as follows if stress σ is applied N cycles.

$$F=1-exp\left(-\left\{\left[a_c{}^{(2-n)/2}+C'(n-2)(\beta\sigma\pi^{0,5})^n(N-1)/(2K_c{}^n)\right]^{2/(2-n)}/a_0\right\}^{-m/2}\right) \quad \text{(D.5)}$$

where

F is the cumulative fracture probability;

a_0 is the scale parameter for the Weibull distribution of the initial crack length (the equivalent crack length obtained by substituting the stress σ with the Weibull scale parameter σ_0 in Equation (D.4) into Equation (D.2);

a_c is the equivalent crack length corresponding to failure with the stress σ;

β is the coefficient related to the crack shape;

m is the Weibull modulus;

σ is the applied stress;

N is the number of cycles;

C' and n are constants;

K_c is the fracture toughness;

π is the number 3,141 592 6… .

D.3 Effect of initial loading

For resonant vibration test, it is difficult to set the amplitude instananeously, but the vibration amplitude gradually increases in the beginning. In this section, the effect of the initial loading procedure is evaluated.

Assuming the amplitude is linearly increased with the number of cycles,

$$\sigma = \alpha N \tag{D.6}$$

where

σ is the applied stress;

α is the constant showing the increasing rate;

N is the number of cycles.

By substituting this equation and the Equation (D.2) to the Equation (D.1), and integrating the equation, the following equation representing the constant increasing amplitude test can be obtained.

$$N_f - \frac{1}{N_f^n} = \frac{a_{c0}}{C'} \frac{2(n+1)}{2-n} \left(\frac{\sigma_f}{\sigma_{c0}} \right)^{-2} \left[1 - \left(\frac{\sigma_f}{\sigma_{c0}} \right)^{2-n} \right] \tag{D.7}$$

where

N_f is the number of the cycles to fracture the sample at the stress σ_f;

C' and n are constants;

σ_f is the stress at fracture;

a_{c0} is the equivalent initial crack length;

σ_{c0} is the static strength.

By comparing the Equation (D.7) to (D.3), the following relationship was derived,

$$N_f \approx (n+1)N \tag{D.8}$$

where

N_f is the number of the cycles to fracture the sample at the stress σ_f;

n is a constant;

N is the number of cycles.

This means the number of cycles applied during the initial loading corresponds to $N_f/(n+1)$ cycles of constant amplitude fatigue test at σ_f. Assuming the resonant frequency of 10 kHz and initial loading time 1 s, the equivalent cycles is only 500 cycles at $n = 20$.

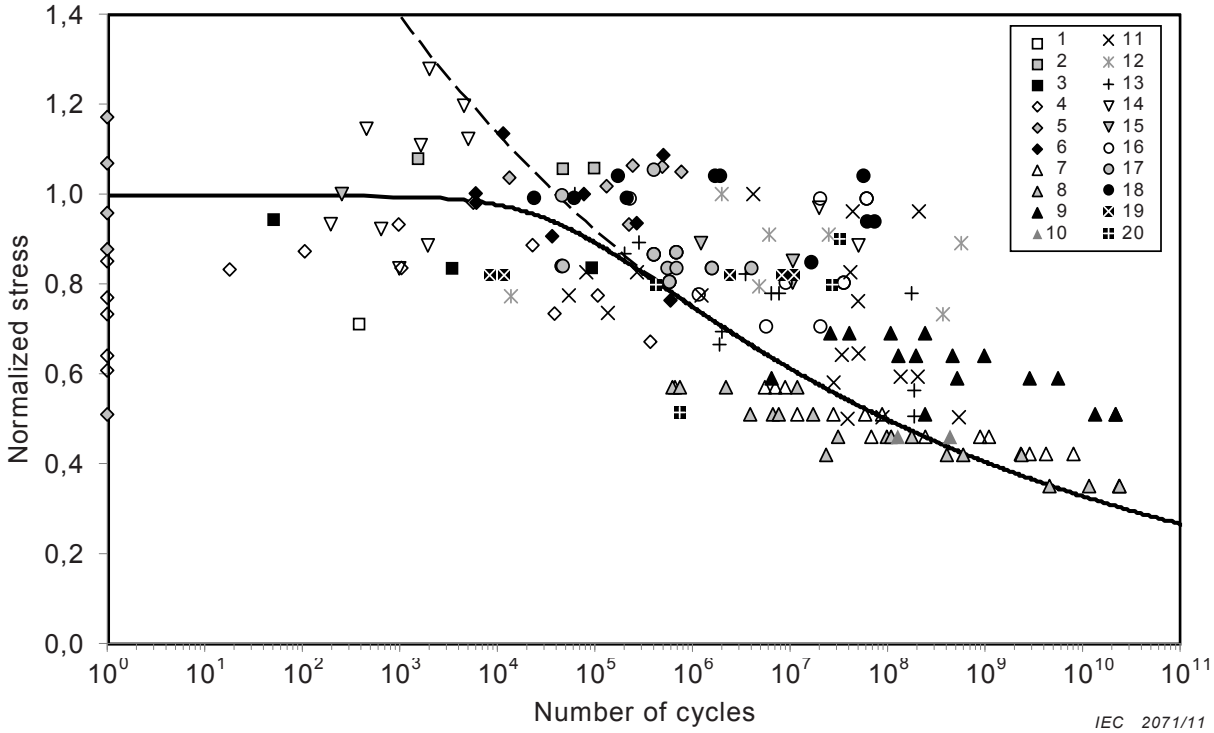
Annex E
(informative)

Analysis examples

E.1 Fatigue test results of silicon

Unlike conventional macro structures, MEMS structures are fabricated from various new materials. To analyze the data from fatigue testing, it thus becomes necessary to understand the differences in fatigue behavior from those of the more familiar metallic materials. Silicon, one of the main structural materials used in MEMS, has a large deviation in both the strength and fatigue life, since silicon structures are fabricated using wet and dry etching processes.

Figure E.1 shows an S-N curve as an example of fatigue test results for silicon. The data were obtained from various organizations and plotted on a single graph. The vertical axis plots the maximum stress during the fatigue tests normalized according to the average failure stress (static strength) with a monotonically increasing load. The horizontal axis plots the number of cycles until failure.



Key

1 Single-crystal <100> 10Hz
2 Single-crystal <110> 10Hz
3 Single-crystal <111> 10Hz
4 Single-crystal <110> 24,7-26,9ºC 85-90%RH 40Hz
5 Single-crystal <110> 24,7-27,0ºC 25-30%RH 40Hz
6 Single-crystal <110> 25,9-26,0ºC 55-65%RH 40Hz
7 Single-crystal <110> 23 ºC 25%RH 39kHz
8 Single-crystal <110> 23ºC 50%RH 39kHz
9 Single-crystal <110> 23 ºC 50%RH 36kHz
10 Single-crystal <110> 23ºC 50%RH 39kHz
11 Single-crystal 23ºC 14-31kHz
12 Single-crystal 100ºC 14-31 kHz
13 Single-crystal 300ºC 14-31kHz
14 Single-crystal 25ºC 50-60%RH 182-196Hz
15 Single-crystal 25ºC 50-60%RH 155-176Hz
16 Polycrystalline 22ºC 80%RH 100Hz
17 Polycrystalline 22ºC 80%RH 250Hz
18 Polycrystalline 22ºC 80%RH 500Hz
19 Single-crystal ICP-RIE 22ºC 80%RH 100Hz
20 Single-crystal Laser microjet 22ºC 80%RH 250Hz

Figure E.1 – Example of fatigue test results for silicon materials

These data were obtained using different testing methods including quasi-static and dynamic loading, under various stress ratios, including fully reversed and pulsating tensile stress. In spite of such the inevitable differences in test conditions and the large scatters in test results, a common tendency can be discerned after the normalization. Unlike the case with metal materials, most of the samples failed after 10^4 cycles even during fatigue testing with stresses at around the average static strength. This is one of the important features of silicon fatigue behavior, and it can be regarded as the main factor impeding fatigue testing for silicon.

E.2 S-N curve fitting

Equation (D.3) was fitted to the whole data plotted in Figure E.1. The solid line in Figure E.1 is the S-N curve showing the results of fitting with the regression parameters a_{c0}/C' and n. The flat region of the line indicates the initial strength, which may correspond to the fact that only a small number of the fatigue failure data was observed below 10^4 cycles. This results shows that Paris' law is valid for silicon even up to the stress level around the fracture strength, where metallic materials shows general yielding. Therefore, the second term in the square brackets on the right hand side of Equation (D.3) cannot be ignored. If this term is ignored, the S-N curve becomes the dashed line which cannot describe the behavior in the region of low fatigue cycles.

E.3 Fatigue life prediction of polysilicon

Figure E.2 shows the fitted results of Equation (D.5) for a tensile fatigue test of polysilicon. Here, the constant β was calculated as 1,12. In this 3D figure, the z axis represents the cumulative fracture probability, the x axis represents the applied stress, and the y axis represents the number of cycles. The mesh of the continuous lines represents the calculated values of Equation (D.5), and the black dots are the test results. The plotted test results are ranked from the shortest to the longest equivalent initial crack length. The calculated values and test results match closely, which strongly suggests that the variation in fatigue life is closely related to the distribution of the static strength.

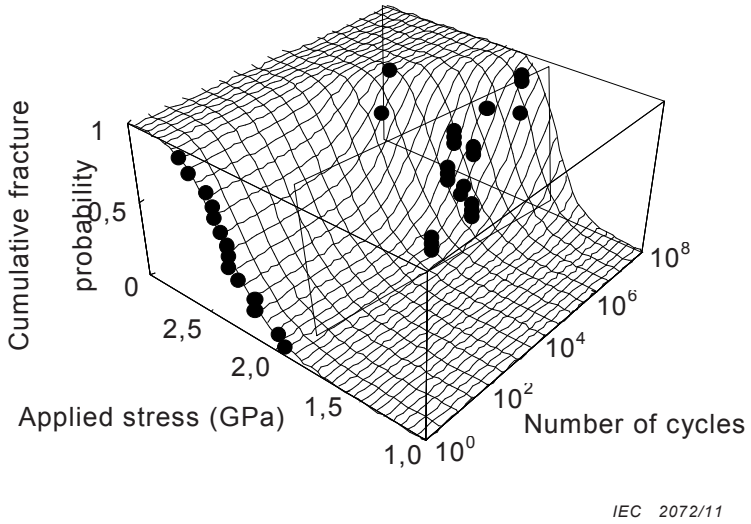


Figure E.2 – Static strength and fatigue life of polysilicon plotted in 3D

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